

Octetonium at the LHC

Chul Kim and Thomas Mehen

Department of Physics, Duke University, Durham, NC 27708, USA

Abstract. Several models of new physics, such as grand unified theories, Pati-Salam models, chiral color models, etc., predict the existence of an $SU(2)_L$ doublet of color-octet scalars (COS). In the Manohar-Wise model, the Yukawa couplings of the COS are assumed to be consistent with Minimal Flavor Violation ensuring constraints from flavor physics are satisfied even for relatively light scalars. In this simple model we consider the production of color singlet bound states of COS that we call octetonium. Octetonium are mainly produced via gluon-gluon fusion and have significant production cross sections at the LHC. They can decay to pairs of gluons or electroweak gauge bosons. If the masses of the octetonia are 1 TeV or less, these states will be visible as resonances in $\gamma\gamma, W^+W^-, ZZ$, and γZ .

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In the Standard Model (SM) electroweak symmetry breaking is accomplished by the introduction of a single color-singlet, $SU(2)_L$ scalar doublet. Over the years many extensions of the SM with richer scalar sectors have been proposed and testing these models is an important goal of LHC physics. One possibility is a scalar sector containing $SU(2)_L$ doublets that are octets rather than singlets under $SU(3)_c$. Many models of new physics contain such particles including grand unified theories, Pati-Salam models, chiral color models, etc. [1].

An important constraint on models of new physics is the absence of flavor changing neutral currents (FCNC) at tree level. Generic theories with TeV-scale particles that can lead to FCNC's are ruled out. One way to ensure that such unwanted effects are not present in new physics models is to impose Minimal Flavor Violation (MFV) [2]. In MFV one demands that all violation of the flavor symmetry of the SM be proportional to the SM Yukawa couplings. Manohar and Wise [3] asked what is the most general scalar sector that is consistent with MFV and found the answer is quite restrictive: the only allowed scalars are those with quantum numbers $(\mathbf{1}, \mathbf{2})_{1/2}$ and $(\mathbf{8}, \mathbf{2})_{1/2}$, i.e. the SM Higgs and color-octet scalars (COS). The simplest model containing COS has the following Yukawa couplings to quarks [3]

$$\mathcal{L}_Y = -\eta_U g_{ij}^U \bar{u}_{Ri} T^A Q_{Lj} S^A - \eta_D g_{ij}^D \bar{d}_{Ri} T^A Q_{Lj} S^{A\dagger} + \text{h.c.}, \quad (1)$$

where

$$S^A = \begin{pmatrix} S^{A+} \\ S^{A0} \end{pmatrix} \quad (2)$$

are the complex color-octet scalar fields, Q_{Lj} is $SU(2)_L$ doublet of quark fields, $u(d)_R$ is an up(down)-type right-handed quark fields. $g_{ij}^{U,D}$ are SM Yukawa coupling matrix elements and $\eta_{U,D}$ are unconstrained complex parameters. Three mass eigenstates of the

color-octet scalar fields are $S^{A\pm}$, $S_R^{A0} = \sqrt{2}\text{Re}S^{A0}$, and $S_I^{A0} = \sqrt{2}\text{Im}S^{A0}$, whose masses at tree level are given by

$$m_{S^\pm}^2 = m_S^2 + \lambda_1 \frac{v^2}{4}, \quad (3)$$

$$m_{S_R^0}^2 = m_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{4}, \quad (4)$$

$$m_{S_I^0}^2 = m_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{4}, \quad (5)$$

where v is the vacuum expectation value of the Higgs field, and m_S , λ_1 , λ_2 , and λ_3 are parameters in the scalar potential [3].

The present experimental constraints on the masses are rather weak. From the CDF search $H \rightarrow b\bar{b}$ plus associated additional b jets [4], Ref. [5] estimated that the lower mass bounds for the COS is ~ 200 GeV when both the couplings η_U and η_D are of order unity. But masses lower than 200 GeV are allowed if η_D is much less than η_U [6]. The production cross section for color-octet particles is much larger at the LHC than at the Tevatron because of the larger energy and higher luminosity for gluon-gluon fusion initiated processes. For color-octet masses in the range 200 - 500 GeV the pair production cross section is of order 10-100 pb [3].

In this proceeding we consider the possibility of forming color singlet bound states of COS which we call octetonium. Formation of bound states is possible if the Yukawa couplings in Eq. (1) are $O(1)$ or smaller. The octetonium production cross section are only an order of magnitude below the pair production cross sections. The dominant decay mode for these states is to two gluon jets. They can also decay to pairs of electroweak gauge bosons, such as W^+W^- , $\gamma\gamma$, γZ^0 and Z^0Z^0 . We will see below that if the COS mass is less than 500 GeV, the cross section for $\gamma\gamma$ is large enough that the octetonium would appear as resonances above the SM background, and we expect this to hold for other final states as well.

Since the COS masses are much larger than Λ_{QCD} , we expect that they will be Coulombic in nature and perturbation theory will be a good guide to some of their properties. Assuming this, the typical velocity of the COS within the octetonium is given by $v \sim N_c \alpha_s(m_S v)$, where N_c is the number of colors. For $m_S = 200 - 1200$ GeV, we find $v = 0.37 - 0.30$ and $\alpha_s(m_S v) = 0.12 - 0.10$. The coupling and velocity are similar to what is found in bottomonium. In order to produce bound states, the formation time must be shorter than the lifetime of the constituents. Under the assumption that the main decay channels are $S^{A+} \rightarrow t\bar{b}$ and $S_{R,I}^{A0} \rightarrow t\bar{t}$ via the Yukawa couplings, the ratio of the formation time to the life time for $S^{A\pm}$ is

$$\frac{\tau_{\text{form}}}{\tau_{\text{life}}} = \frac{2\Gamma[S^{A\pm}]}{B.E.} \sim 0.08|\eta_U|^2 - 0.6|\eta_U|^2, \quad (6)$$

for m_{S^\pm} in the range 200-500 GeV. Here $B.E.$ is the binding energy which is estimated to be $m_S N_c \alpha_s(m_S v)^2/4$. Similar results hold for the time ratio of the neutral color-octet. So when $|\eta_U| < 1$, we see that the formation of the bound state is possible.

In this proceeding we will consider only three octetonium such as O_+^0 , O_R^0 , and O_I^0 which are the color-singlet bound states of $S^{A+}S^{A-}$, $S_R^{A0}S_R^{A0}$, and $S_I^{A0}S_I^{A0}$ respectively.

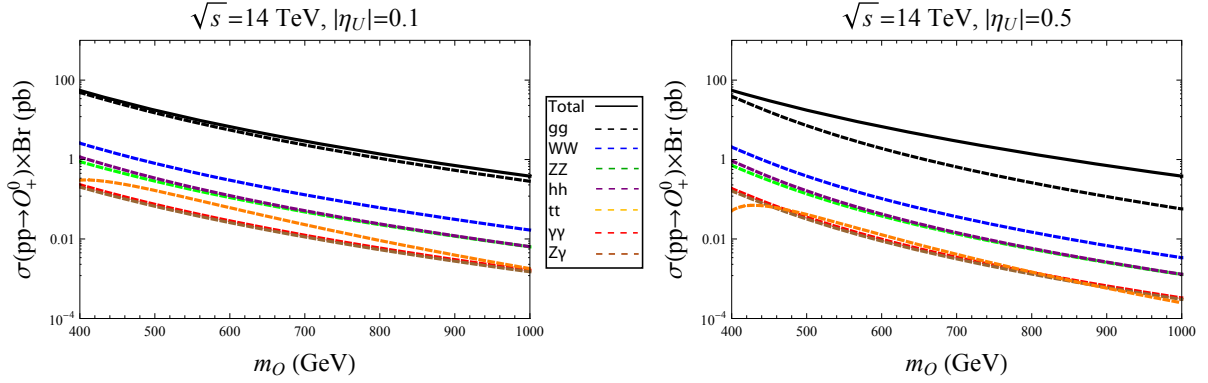


FIGURE 1. LHC cross sections for $pp \rightarrow O_+^0 \rightarrow X$, where X is a two-body final state.

The octetonium wavefunction is

$$|O_+^0(P)\rangle = \frac{\delta^{AB}}{\sqrt{N_c^2 - 1}} \sqrt{\frac{2}{m_O}} \int \frac{d^3k}{(2\pi)^3} \tilde{\psi}(k) |S^{A+}(P/2 + k) S^{B-}(P/2 - k)\rangle, \quad (7)$$

for O_+^0 , where P^μ is the momentum of O_+^0 , k^μ is the relative momentum of the S^A in the bound state, and $\tilde{\psi}(k)$ is the momentum space wave function. For $O_{R,I}^0$, the same definition can be applied, but divided by $\sqrt{2}$.

At parton level, the scattering cross section for the bound state is

$$\hat{\sigma}[gg \rightarrow O_+^0] = 2\hat{\sigma}[gg \rightarrow O_R^0] = \frac{9\pi^3 \alpha_s^2 (2m_S)}{2m_S \hat{s}} |\psi(0)|^2 \delta(\hat{s} - m_O^2) \quad (8)$$

where \hat{s} is the partonic center of mass energy squared. For the wave function at the origin squared we use the Coulombic approximation

$$|\psi(0)|^2 = \frac{N_c^3 \alpha_s^3 (m_S v) m_S^3}{8\pi}. \quad (9)$$

If the Yukawa coupling η_U is smaller than one so that the S^A are sufficiently long lived, the dominant decay channel for the octetonia is via annihilation of COS to two gluons. However, it is doubtful that they could be discovered as a resonance in the two jet cross section since the SM background is enormous. More promising would be to search in rare decays to final states with two electroweak gauge bosons such as $\gamma\gamma$, W^+W^- , γZ^0 , and $Z^0 Z^0$. For these final states backgrounds are much smaller than for two jets. In Fig. 1, we show the scattering cross sections for $gg \rightarrow O_+^0 \rightarrow X$ where X are several two body final states. The branching fractions and the analytic expressions for the decay rates can be found in Ref. [7].

To check if the signal for the bound states will be visible above SM backgrounds we calculate the differential scattering cross section for $pp \rightarrow O_+^0 \rightarrow \gamma\gamma$ process with respect to $m_{\gamma\gamma}$. Then we integrate this in the range $(m_{\gamma\gamma} - \Delta/2, m_{\gamma\gamma} + \Delta/2)$ employing the Breit-Wigner profile. Here we chose $\Delta = 6$ GeV which is the expected energy resolution below $m_{\gamma\gamma} = 1$ TeV in the ATLAS experiment [8]. This is compared with the SM contribution to

TABLE 1. $\sigma_{\text{res}}[pp \rightarrow O_+^0 \rightarrow \gamma\gamma]$ is the resonant cross section for photons with $|\eta| < 2.4$ and $m_{\gamma\gamma}$ within ± 3 GeV of the resonance mass for different values of $m_{O_+^0}$, $\sigma_{\text{SM}}[pp \rightarrow \gamma\gamma]$ is the SM contribution in the same region.

	400 GeV	600 GeV	800 GeV	1000 GeV
$\sigma_{\text{res}}[pp \rightarrow O_+^0 \rightarrow \gamma\gamma](\text{fb}), \eta_U = 0.1$	187	24	5.1	1.4
$\sigma_{\text{res}}[pp \rightarrow O_+^0 \rightarrow \gamma\gamma](\text{fb}), \eta_U = 0.5$	149	7.7	1.1	0.23
$\sigma_{\text{SM}}[pp \rightarrow \gamma\gamma](\text{fb})$	12.0	2.2	0.64	0.23

this process in Table 1. The signal is dominant over the SM backgrounds for octetonia in the mass range 400 - 1000 GeV.

To summarize, we have argued that the COS can form strongly bound color-singlet states called octetonia provided the Yukawa couplings of the COS to SM quarks is $O(1)$ or smaller. This condition is required so that the COS do not decay to heavy quarks before they have time to form a resonance via their strong Coulomb attraction. We have computed production cross sections for octetonia at the LHC which turned out to be quite large as well as two body-decay rates to SM particles. The decay to two gluons dominates over others, but rare decays to SM electroweak bosons are also significant. In particular we showed that the process $pp \rightarrow O_+^0 \rightarrow \gamma\gamma$ will be visible as a resonance above the SM background when the octetonia masses are in the range 400-100 GeV. Though we have not done explicit calculations, we expect similar results for W^+W^- , γZ^0 , and $Z^0 Z^0$. The higher order QCD corrections including soft gluon resummation for the precise prediction of total and differential scattering cross sections will be available in the near future [9].

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